Renewable and Sustainable Energy Reviews 29 (2014) 286–300

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An economic and environmental assessment for selecting the optimum new renewable energy system for educational facility

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ARTICLE INFO

Article history:
Received 11 January 2012
Received in revised form
12 August 2013
Accepted 24 August 2013
Available online 19 September 2013

Keywords:
New renewable energy
Energy consumption
Educational facility
Energy simulation
Life cycle Co_2

ABSTRACT

With the world's attention focused on climate change, the United Nations Framework Convention on Climate Change provides the basis for global action to encourage sustainable development. A wide variety of measures are being taken in South Korea in line with this trend, but new and renewable energy (NRE) have been highlighted as sustainable energy sources. This study aims to assess the economic and environmental effects of the use of NRE for selecting the optimum NRE system in educational facilities. Towards this end, the following were done: (i) selection of facility and its applicable NRE system type; (ii) calculation of the energy generation by the NRE systems via energy simulation; (iii) life cycle cost analysis for the economic evaluation on the NRE systems; (iv) life cycle assessment for the environmental evaluation on the NRE systems; (v) using the net present value and the savings-to-investment ratio, comprehensive evaluation of the economic and environmental effects on the NRE systems.

The results of this study can be used to (i) determine which NRE system is most appropriate for educational facilities; (ii) calculate the payback period for a certain investment; (iii) decide which location is proper for the implementation of an NRE system considering the characteristics of the regional climate; and (iv) select energy- and cost-efficient elementary schools where the NRE system can be applied.

Contents

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.08.061

1. Introduction

Faced with the problem of global warming and climate change, efforts to save energy and to reduce carbon dioxide (CO_2) emissions are being exerted all over the world. Under such circumstances, researches on new and renewable energy (NRE) are also actively being done [1]. As radioactive pollution and energy storage problems were highlighted in the wake of the nuclear-power-plant accident in Fukushima, Japan, the interest in NRE has been increased. Germany enacted the Renewable Energy Source Act in 2000, established the Sustainable Energy Supply Scenario, and set the target of replacing 50% of its total energy generation with NRE by 2050 [2]. China proposed the use and development of renewable energy as a prior task to be promoted in the energy area, and established a plan to invest US$740 billion in the next 10 years to increase the proportion of NRE by 2020. The U.S. established a plan to invest US$150 billion to achieve its target of replacing 25% of its total energy generation with NRE by 2025 [3–5]. For South Korea, the South Korean government is promoting various programs to expand the distribution of NRE, such as the 1 Million Green Homes Program, Regional Deployment Subsidy Program, Loans and Tax Incentive Program, and Mandatory Renewable Energy Installation Program. In particular, the implementation of the Mandatory Renewable Energy Installation Program was limited to new construction projects but was expanded in April 2011 to include the extension and reconstruction works of existing buildings [6–8].

In South Korea, NRE has been introduced to education facilities through programs for the improvement of the educational environment and the establishment of green schools and eco-schools. As the floor area ratios of educational facilities are relatively smaller compared to those of other facilities, such as multi-family housing or offices, the effect of the introduction of NRE to educational facilities is expected to be greater. Nevertheless, as it is being promoted only as part of the educational-facility improvement program, there is a limit to the expansion of the distribution of NRE. Further, there is no clear general method for assessing the economic and environmental effects of the introduction of NRE.

The previous studies on NRE system have been conducted from a variety of perspectives. First, the life cycle cost (LCC) and the life cycle cost CO_2 ($LCCO_2$) analyses of NRE systems have been conducted [9–17]. The application of the photovoltaic (PV) system to the roof of a hotel reduced the $LCCO_2$ emissions by 13–21% compared with the conventional system [9]. The energy payback period was analyzed through the sensitivity study of the electricity generation of stand-alone and grid-connected PV systems [10]. In another study, LCC and $LCCO_2$ analyses of the ground source heat pump (GSHP) system and the existing oil boiler system were performed. As opposed to the existing oil boiler system, it was determined that about 50% of the $LCCO_2$ emissions can be saved by applying the GSHP system, and that LCC savings amounting to over 50,000–90,000 Japanese yen/year can be attained [11]. These studies simultaneously considered the economic and environmental effects by calculating the energy generated by NRE system and converting it to CO_2 emissions. The amounts of CO_2 emissions generated in the construction, operation and maintenance phases of NRE systems, however, were not considered.

Second, a life cycle assessment (LCA) on the materials used in each NRE system has been conducted to assess the environmental effects of the NRE systems [18–22]. To assess the environmental effects of the renewable electricity systems (e.g., PV system, wind system, geothermal, steam turbine, etc.), the renewable heat systems (e.g., heating plant, central heating, solar thermal collectors, etc.), and the conventional system, the amounts of CO_2 emissions were analyzed via LCA [19]. LCA was also conducted to assess the environmental effect of the PV system by type such as polycrystalline, mono-crystalline, and thin films [20]. LCA was performed to assess the environmental impacts of the PV and maize-biogas systems. From the long-term point of view, the appropriate strategies of the aforementioned two systems were also proposed [21]. These studies deal with the CO_2 generated in the process of material production for the NRE system. After the introduction of the NRE system, however, the amounts of CO_2 emissions in the operation and maintenance phases were not considered.

Third, the techno-economic analysis, experimental evaluation, and future outlook of NRE system have been conducted [23–29]. To analyze the technical feasibility and financial viability of grid-connected or stand-alone PV system, a computerized renewable energy assessment tool ‘*RETScreen*’ was used [23,24]. To conduct the techno-economic appraisal of heat pump systems (e.g., ground-coupled, air-coupled, biogas, and solar heat pump) for space heating and cooling, experimental system was installed and tested [25–27]. To establish the introduction strategy of PV system, a study was conducted to predict the scenarios in terms of the pessimistic, optimistic and realistic, and very optimistic views for three factors: initial investment cost, market penetration, and environmental performance [28]. Further, the economic effect of the introduction of an NRE system was assessed considering the price of the NRE system and the volatility of carbon price [29]. Although these studies conducted a validity test reflecting the uncertainty of the introduction of the NRE system from various perspectives, the economic and environmental effects of the introduction of the NRE system were not demonstrated.

Nevertheless, there have been insufficient studies providing a comprehensive method of assessing the economic and environmental effects of the NRE systems, and executing LCA based on such effects. In this study, an economic and environmental assessment for selecting the optimum NRE system was conducted. Educational facilities were also selected as a case study because their NRE introduction effects are expected to be large as their floor area ratios are small compared to the other facilities included in the Mandatory Renewable Energy Installation Program.

This paper consists of the following five steps: (i) selection of facility and its applicable NRE system type; (ii) calculation of the energy generation by the NRE systems via energy simulation; (iii) life cycle cost analysis for the economic evaluation on the NRE systems; (iv) life cycle assessment for the environmental evaluation on the NRE systems; (v) using the net present value and the savings-to-investment ratio, comprehensive evaluation of the economic and environmental effects on the NRE systems.

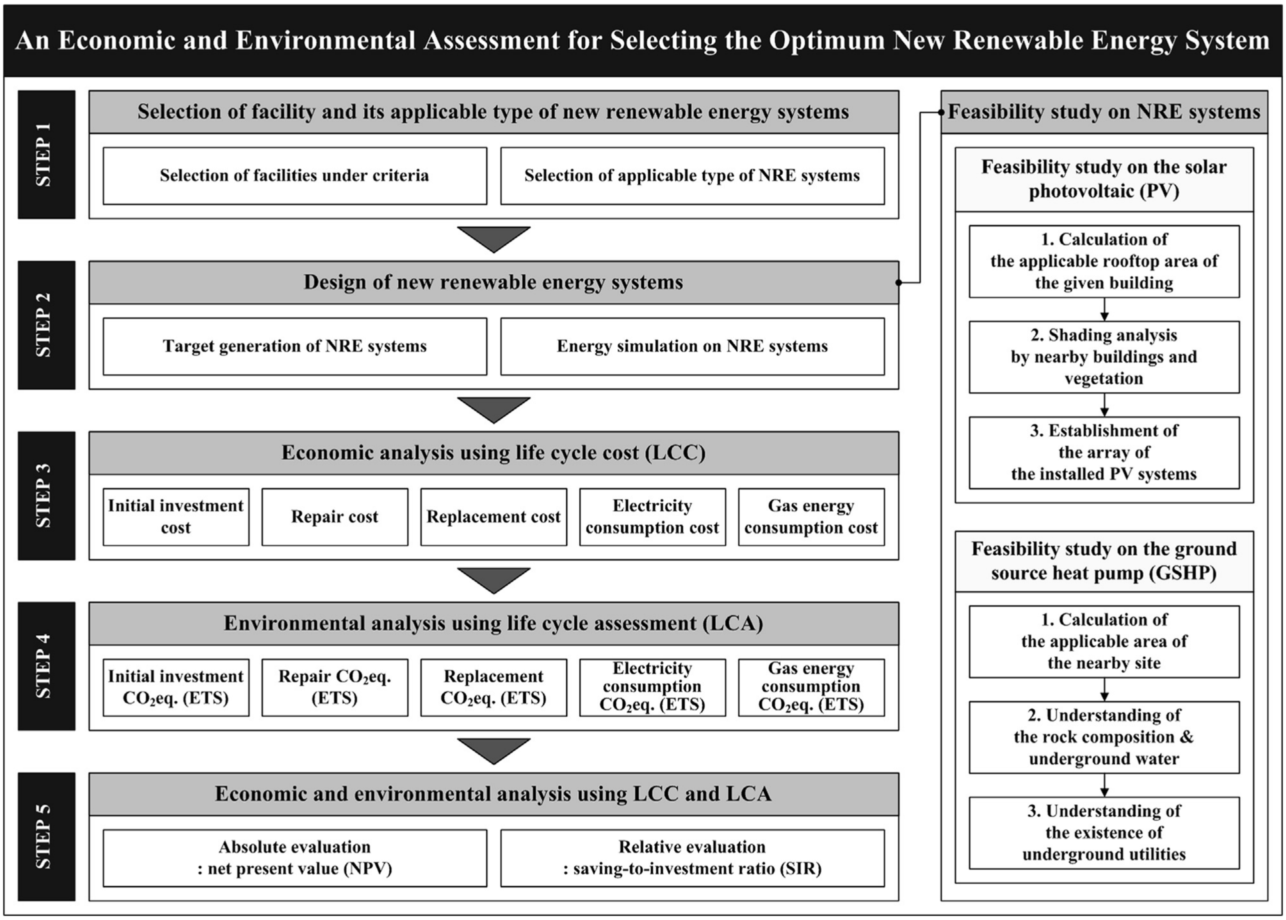

Fig. 1. Research framework.

2. Research framework

The purpose of this study was to conduct an economic- and environmental-effect assessment for the NRE systems. The study process is shown in Fig. 1, and below are its details.

First, the facilities that the NRE systems are applied to and their applicable NRE system type were selected, after which the facility usage data were examined and utilized as basic data for the energy simulation in the next stage. Then a market research on the NRE system was conducted, and the type of NRE system that is applicable to the corresponding facility was selected.

Second, energy simulation using the NRE system selected in the previous stage was conducted to compute the amount of energy produced or substituted by such system, and the obtained value was used in the LCC analysis. The amount of energy produced or substituted, however, was converted to the amount of CO_2 emissions and was used in the $LCCO_2$ analysis.

Third, economic evaluation was conducted before and after the introduction of the NRE system, via LCC analysis. The validity of the significant cost of ownership was secured through a market research on the NRE system and an interview with the suppliers.

Fourth, environmental evaluation was conducted before and after the introduction of the NRE system, via LCA. The composition of the materials was determined through the analysis of a bill of quantity on the NRE systems, and the amount of CO_2 emissions in the material production phase was calculated. The amount of CO_2 emissions by the repair and replacement work in the operation and maintenance phase was also calculated.

Fifth, using the results obtained from the LCC analysis and LCA, comprehensive economic and environmental evaluation was conducted before and after the introduction of the NRE systems. The NPV was used as an absolute index, and the SIR was utilized, with the return on investment (ROI) as a relative index.

3. Selection of facility and its applicable type of new renewable energy systems

3.1. Selection of facilities under criteria

To conduct an economic- and environmental-effect assessment for the NRE systems in this study, a facility that has actually applied an NRE system was selected as a case study. The following criteria were applied to select the cases:

- Educational facilities with an over 5.44% energy-saving rate among the educational facilities applying an NRE system (average energy-saving rate of the educational facilities that applied an NRE system as part of the exemplary Eco-School Project in 2009: 5.44%) [30];
- Educational facilities that introduced an NRE system at least a year ago, and that continuously implement the actually-measured energy generation data. The reasons for this are as follows: (i) based on the standards provided by the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE), at least one year of actually-measured data should be used for energy simulation to be valid; and (ii) as

Table 1
Description of "S" and "I" Elementary School.

Class	"S" Elementary School	"I" Elementary School
Year established	2003	1982
Location	Seoul	Goyang
No. of buildings	4	2
Gross area (m^2)	11,406.80	7895.2
Type of structure	Steel-reinforced concrete	Steel-reinforced concrete
Air-conditioning area (m^2)	7490.10	5367.9
Cooling schedule	May–September	May–September
Heating schedule	January-April, October–December	January–April, October–December
Electricity consumption (kWh)	443,954.67	353,353.67
Gas energy consumption (m^3)	40,487.00	6401.00
CO_2 emission from electricity consumption (tCO_2)	197.46	157.16
CO_2 emission from gas energy consumption (tCO_2)	90.31	14.28

South Korea has four seasons, the actual data reflecting the seasonal characteristics are required; and

- Educational facilities that implemented the gas-engine-driven-heat-pump (GHP) or electric-heat-pump (EHP) system as an air cooling and heating systems (to compare the GHP and EHP replacement effect according to the introduction of the GSHP system).

Based on the above criteria, two facilities were selected for the study: (i) "S" Elementary School, located in Seongbuk-gu, Seoul, South Korea; and (ii) "I" Elementary School, located in Ilsan-gu, Goyang-si, South Korea. "S" Elementary School introduced a 44 kW PV system in December 2009 and has replaced 7.5% of the annual energy consumption with PV energy. Moreover, it uses the GHP system as its cooling and heating system. "I" Elementary School, on the other hand, implemented the 42 kW PV system in December 2009 and has replaced 11.5% of the annual energy consumption with PV energy. Moreover, it uses the EHP system as its cooling and heating system.

Table 1 provides data about "S" and "I" Elementary School with regard to their characteristics and energy consumption.

3.2. Selection of applicable type of new renewable energy systems

There are nine types of NRE systems: solar photovoltaic energy (PV), solar thermal energy (STE), ground source heat pump (GSHP), wind energy (WE), fuel cell, hydrogen energy, bio energy, technology for energy recovery from waste, and liquefied petroleum gas (LPG). Of these, four are generally applied to buildings: PV, STE, GSHP, and WE. In this study, the PV and GSHP systems were selected as applicable NRE systems to "S" and "I" Elementary School. The STE and WE systems were excluded from this study for the reasons cited below.

- The STE system is an NRE system that replaces hot-water energy. It is thus generally applied to educational facilities, including dormitories [13,31]. As the schools that were selected in this study did not have dormitories, however, they did not have much hot-water energy consumption. Further, the period from December to February, when the hot-water energy consumption is high, is the winter and spring vacation. Under these circumstances, interview was made with an STE system expert, and it was found that it is not suitable to apply the STE system to "S" and "I" Elementary School.
- The WE system is an NRE system that transforms energy generated by wind into electricity. According to the guideline provided by Korea Energy Management Corporation (KEMCO), the recommended wind velocity for applying a small WE system to a building is 4.5–5.0 m/s. The average wind velocity in the region where the buildings are located, however, is 2.43 m/s, which does not meet the implementation standard. As such, the WE system was not considered suitable for the buildings.

Table 2
Profile of the PV system (200 W).

Classification		PV System
Model name		SM-200 PDO
Output (w)		200
Module efficiency (%)		15.2
Miscellaneous losses (%)		3
Size(mm)	Width (B)	980
	Length (A)	1460
	Thickness	38

3.2.1. Selection of PV system

According to the materials of the solar cell, the PV system is divided into the crystalline and amorphous silicon solar cells. Among the various crystalline silicon solar cells [32], the mono-crystalline and multi-crystalline solar modules are currently the most generally used in the South Korean market. As the schools that were selected for this study had actually applied the 200 W multi-crystalline module, such module was selected as the module to be applied to the energy simulation. The validity of the simulation result is reviewed by comparing the actual energy produced by the PV system and that produced in the energy simulation [24,33]. Table 2 shows the profile of the multi-crystalline module found from the market research.

3.2.2. Selection of GSHP system

The GSHP system is classified into the closed-loop vertical-type geothermal-energy system and the closed-loop horizontal-type geothermal-energy system, according to the type of holes drilled as part of a geotechnical investigation or environmental site assessment. Unlike the closed-loop horizontal-type geothermal-energy system, the closed-loop vertical-type geothermal-energy system does not largely rely on the geological and regional characteristics, and the required area for its establishment is small [34]. As the areas of the two selected schools′ playgrounds are large, there was no problem applying the closed-loop horizontal-type geothermal-energy system. Considering, however, that the systems can be expanded in the future, it was assumed that the two schools apply the closed-loop vertical-type geothermal-energy system that has higher efficiency per area [35,36]. The air cooling and heating coefficient of

Table 3
Energy consumption and CO_2 emission in "S" and "I" Elementary School.

Monthly	"S" Elementary School					"I" Elementary School				
	Electricity consumption		Gas energy consumption		Total CO_2 emission (tCO_2)	Electricity consumption		Gas energy consumption		Total CO_2 emission (tCO_2)
	kWh	CO_2 emission (tCO_2)	m^3	CO_2 emission (tCO_2)		kWh	CO_2 emission (tCO_2)	m^3	CO_2 emission (tCO_2)	
Jan. 2009	50,020.67	22.25	7757.90	17.30	39.55	32,498.33	14.45	1022.00	2.28	16.73
Feb. 2009	44,579.67	19.83	3998.05	8.92	28.75	31,338.67	13.94	1716.00	3.83	17.77
Mar. 2009	42,443.33	18.88	2917.13	6.51	25.38	25,942.33	11.54	1546.00	3.45	14.99
Apr. 2009	44,249.00	19.68	570.61	1.27	20.95	37,383.33	16.63	793.00	1.77	18.40
May. 2009	40,536.00	18.03	238.19	0.53	18.56	33,673.00	14.98	247.00	0.55	15.53
Jun. 2009	27,180.67	12.09	2756.57	6.15	18.24	29,728.67	13.22	138.00	0.31	13.53
Jul. 2009	30,931.33	13.76	5722.69	12.76	26.52	30,237.67	13.45	80.00	0.18	13.63
Aug. 2009	31,983.67	14.23	4322.92	9.64	23.87	29,138.67	12.96	57.00	0.13	13.09
Sep. 2009	28,136.00	12.51	3431.96	7.66	20.17	23,388.33	10.40	50.00	0.11	10.51
Oct. 2009	31,718.67	14.11	499.00	1.11	15.22	24,881.00	11.07	68.00	0.15	11.22
Nov. 2009	28,694.33	12.76	2740.74	6.11	18.88	25,709.00	11.43	204.00	0.46	11.89
Dec. 2009	43,481.33	19.34	5531.23	12.34	31.68	29,434.67	13.09	480.00	1.07	14.16
Sum	443,954.67	197.46	40,487.00	90.31	287.76	353,353.67	157.16	6401.00	14.28	171.44

performance, also called as the COP, of the closed-loop vertical-type geothermal-energy system are 5.17 and 4.81, respectively.

4. Design of new renewable energy systems

4.1. Target generation of new renewable energy systems

"S" and "I" Elementary School introduced the PV system in December 2009. To compute the target energy generation of the NRE system, the amount of energy consumption by energy source in January–December 2009, one year before the PV system was introduced, was analyzed. As the units of electricity and gas energy are different, the electricity and gas energy consumptions were converted to the quantity of CO_2 emissions to unify the units. Eqs. (1) and (2) were used [37,38].

$$\begin{aligned} &\text{The amount of } CO_2 \text{ emission from electric energy consumption } (tCO_2)\\ &= (\text{The yearly amount of electric energy consumption (kWh)})\\ &\times\left(\text{The ratio of the carbon emission factor of electric energy } \left(\frac{tC}{kWh}\right)\right)\\ &\times\left(\text{The ratio of the molecular weight of } CO_2 \text{ to carbon } \left(\frac{tCO_2}{tC}\right)\right) \end{aligned} \tag{1}$$

where, the ratio of the carbon emission factor of electric energy is 0.0001213tC/kWh, and the ratio of the molecular weight of CO_2 to carbon is $44tCO_2/12tC$.

$$\begin{aligned} &\text{The amount of } CO_2 \text{ emission from gas energy consumption } (tCO_2)\\ &= (\text{The yearly amount of gas energy consumption } (m^3))\\ &\times\left(\text{The ratio of the carbon emission factor of gas energy } \left(\frac{tC}{m^3}\right)\right)\\ &\times\left(\text{The ratio of the molecular weight of } CO_2 \text{ to carbon } \left(\frac{tCO_2}{tC}\right)\right) \end{aligned} \tag{2}$$

where, the ratio of the carbon emission factor of gas energy is $0.0006083tC/m^3$, and the ratio of the molecular weight of CO_2 to carbon is $44tCO_2/12tC$.

Table 3 shows the electricity and gas energy consumption and the quantity of CO_2 emissions using Eqs. (1) and (2).

First, "S" Elementary School introduced the 44 W PV system in December 2009 and replaced 7.5% of its annual energy consumption with PV energy. Therefore, the target generation of the NRE system was set at 7.5% of the annual energy consumption. That is, over 7.5% reduction of the quantity of CO_2 emitted by energy consumption was targeted, which is equivalent to $21.58tCO_2$. It was converted to 48.53 MWh electricity and 9676 m^3 gas energy.

Second, "I" Elementary School introduced the 42 W PV system in December 2009 and replaced 11.5% of its energy being consumed annually with PV energy. Therefore, the target generation of the NRE system was set at 11.5% of the energy being consumed annually. That is, over 11.5% of the quantity of CO_2 emitted by energy consumption was targeted, which is equivalent to $18.86tCO_2$. It was converted to 42.40 MWh electricity and 8454 m^3 gas energy.

4.2. Energy simulation on new renewable energy systems

4.2.1. Validation of the simulation

The PV system is an NRE system that can produce electricity. The target generation was set to replace 7.5% and 11.5% of the annual energy consumed by "S" and "I" Elementary School, respectively, by introducing the NRE system. Table 4 compares the actual electricity generation of the PV system established in "S" and "I"

Table 4
Comparison between actual electricity generation and simulation-based electricity generation.

Monthly	"S" Elementary School				"I" Elementary School			
	Actual electricity generation (kWh)	Simulation-based electricity generation (kWh)	Error (%)	CV (RMSE) (%)	Actual electricity generation (kWh)	Simulation-based electricity generation (kWh)	Error (%)	CV (RMSE) (%)
Jan. 2010	3436	3482	1.3%	13.43%	4040	3213	20.5%	14.27%
Feb. 2010	3947	3956	0.2%		3449	3671	6.4%	
Mar. 2010	4204	4685	11.4%		3208	4404	37.3%	
Apr. 2010	5007	5044	0.7%		4260	4773	12.0%	
May. 2010	5298	5101	3.7%		4462	4868	9.1%	
Jun. 2010	3072	4361	42.0%		4049	4167	2.9%	
Jul. 2010	3548	3446	2.9%		3551	3286	7.5%	
Aug. 2010	3420	3877	13.4%		3343	3685	10.2%	
Sep. 2010	3918	4112	5.0%		3602	3879	7.7%	
Oct. 2010	4785	4276	10.6%		4255	3997	6.1%	
Nov. 2010	4068	3243	20.3%		3608	2999	16.9%	
Dec. 2010	3249	3055	6.0%		2791	2814	0.8%	

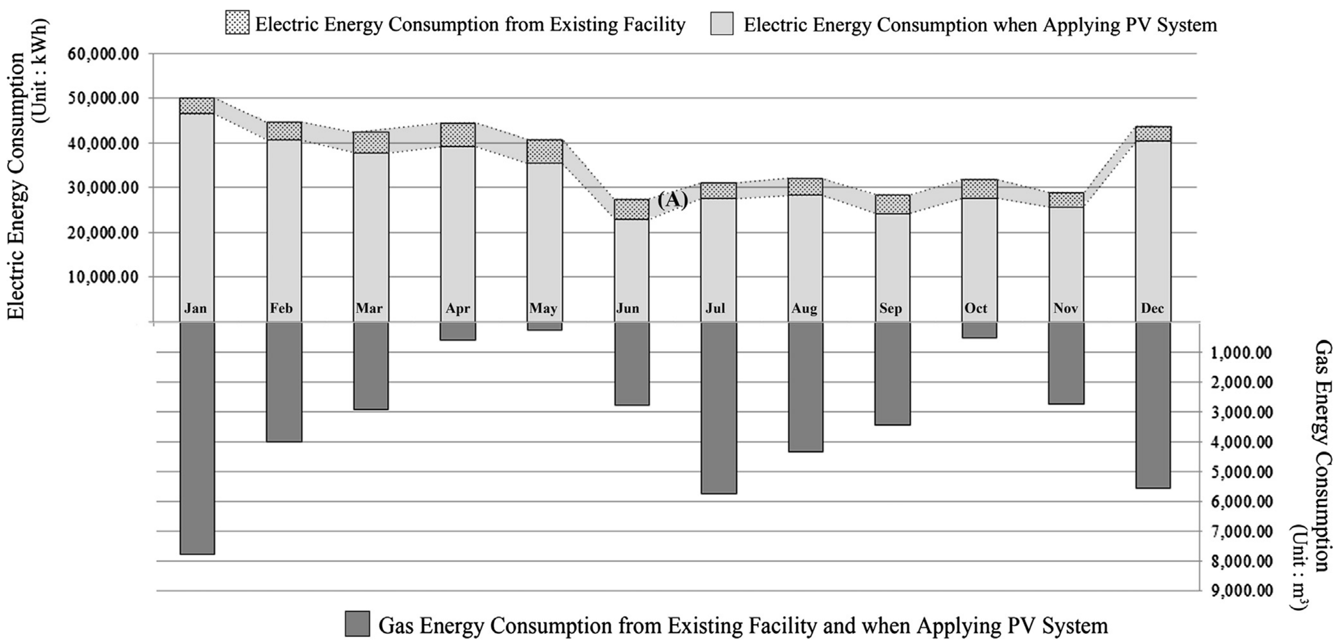

Fig. 2. Effects of the PV system in "S" Elementary School.

Elementary School for one year (2010) with simulation-based electricity generation.

To secure the validity of the energy simulation results, the coefficient of variation of the root mean square error (CV(RMSE)) proposed by ASHRAE was computed using eq. (3). The validity of the energy simulation was secured only when the result was within 25% [39].

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{n} (AEG_i - SEG_i)^2 \times \frac{1}{n}}}{\sum_{i=1}^{n} AEG_i \times \frac{1}{n}} \times 100 \tag{3}$$

where, $CV(RMSE)$ is the coefficient of the variation of the root mean square error, AEG is the actual electricity generation, SEG is the simulation-based electricity generation, and n is the number of data (months).

The CV(RMSE) of "S" and "I" Elementary School were yielded at 13.43% and 14.27%, respectively. Both cases met the required value within the 25% margin of error. Thus, the validity of the energy simulation was secured.

4.2.2. *Effects of photovoltaic system*

Fig. 2 shows the energy consumption by energy source of "S" Elementary School before and after the introduction of the PV system. The shaded area indicated as (A) is the reduced amount of electricity consumption through the PV system. That is, it is the amount of electricity produced by the PV system, which is about 48.65 MWh (Note that as the PV system is an NRE system that produces electricity, it does not influence gas energy consumption.)

Fig. 3 shows the energy consumption by energy source of "I" Elementary School before and after the introduction of the PV system. The shaded area indicated as (A) is the reduced amount of electricity

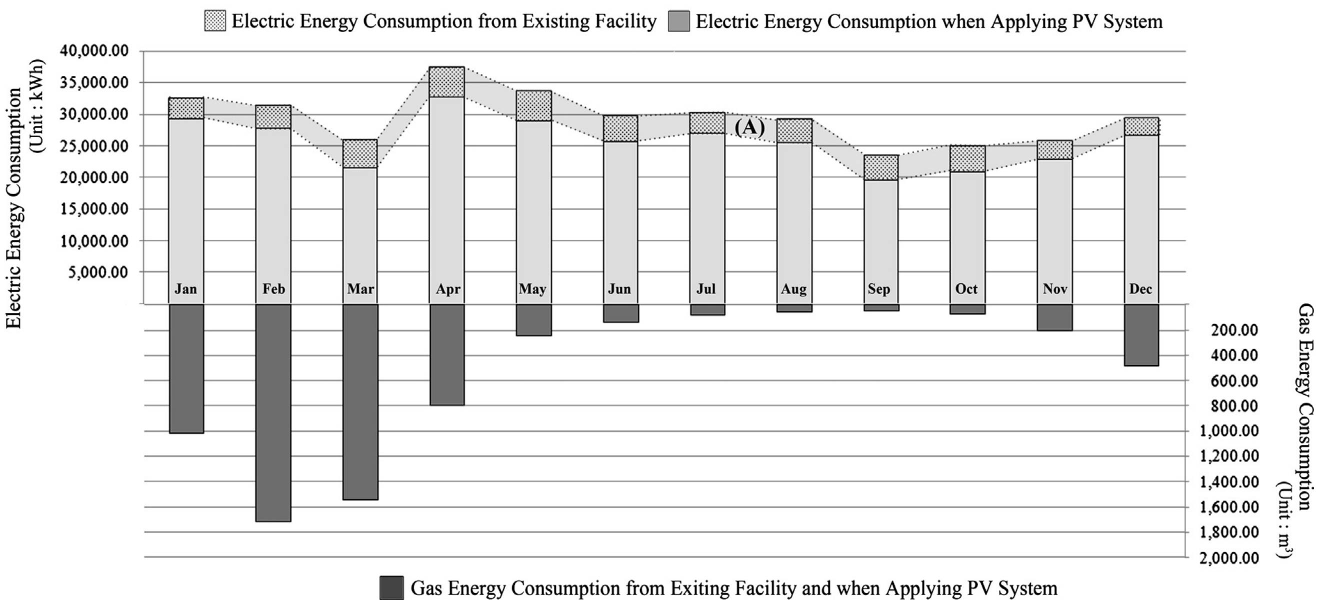

Fig. 3. Effects of the PV system in “I” Elementary School.

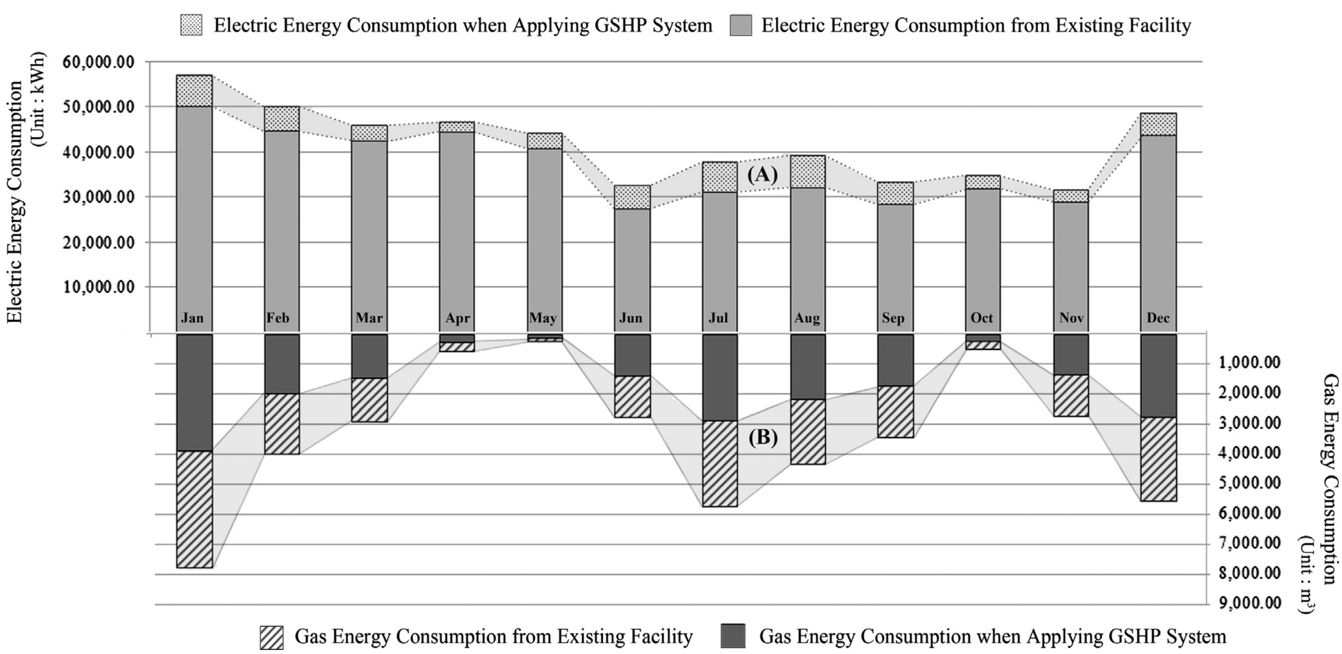

Fig. 4. Effects of the GSHP system in “S” Elementary School.

consumption through the PV system. That is, it is the amount of electricity produced by the PV system, which is about 45.76 MWh.

4.2.3. Effects of ground source heat pump system

The GSHP system is an NRE system that can replace heating and cooling energy. “S” and “I” Elementary School set the target generation to replace 7.5% and 11.5% of their annual energy consumption, respectively. When operating the GSHP system, however, it is necessary to set the target generation considering the additional electricity needed to run the system. Therefore, such additional electricity was considered in establishing the target generation, and below are the standards for setting the target generation for the introduction of the GSHP system in each schools.

- The cooling and heating system of “S” Elementary School was the GHP system, which uses gas energy for its fuel. Such system was replaced by the GSHP system, but based on the energy simulation result, about 61.0 MWh electricity is additionally being consumed to operate the GSHP system (32.0 MWh for heating, 29.0 MWh for cooling). Converted to the quantity of CO_2 emissions, it is about 9.4% of the annual energy consumption of the school. Thus, 9.4% was added to the previously set target generation of 7.5%, and the target generation was therefore reset to about 16.9% of the annual energy consumption of the school. To meet this target, it was determined that the GSHP system needs to replace 55.0% of the cooling and heating energy being consumed by the school based on the GHP system.
- The cooling and heating system of “I” Elementary School was the EHP system, which uses electricity for its fuel. Such system was replaced by the GSHP system, but based on the energy

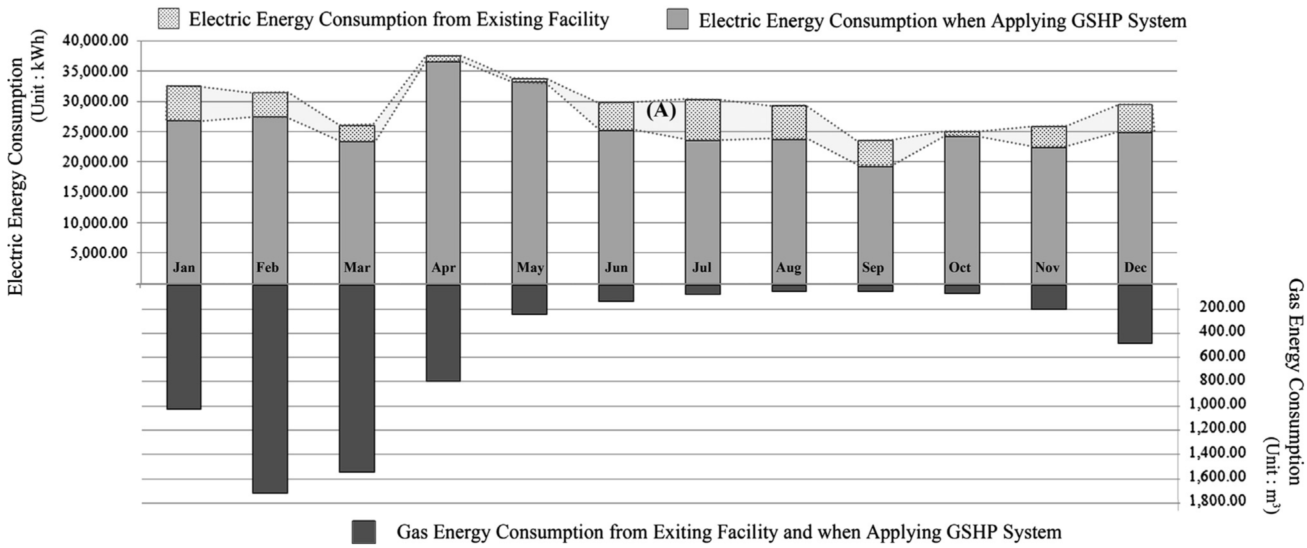

Fig. 5. Effects of the GSHP system in "I" Elementary School.

Table 5
Significant cost of ownership for LCC analysis.

Classification	"S" Elementary School		"I" Elementary School	
	PV	GSHP	PV	GSHP
Initial investment cost (US$)	124,293	102,314	120,729	108,808
Government subsidy	Half of the initial cost	Half of the initial cost	Half of the initial cost	Half of the initial cost
Repair cost and cycle	0.5% of the initial cost per year	1.5% of the initial cost per year	0.5% of the initial cost per year	1.5% of the initial cost per year
Replacement cycle (years)	25	40	25	40
Annual energy consumption (MWh)	0	61.0	0	56.60

simulation result, about 56.6 MWh electricity is additionally being used to run the GSHP system (32.2 MWh for heating, 24.4 MWh for cooling). Converted to the quantity of CO_2 emissions, it is about 14.7% of the annual energy consumption of the school. Thus, 14.7% was added to the previously set target generation of 11.5%, and the target generation was therefore reset to about 26.2% of the annual energy consumption of the school. To meet this target, it was determined that the GSHP system needs to replace 100% of the cooling and heating energy being consumed by the school based on the EHP system.

Fig. 4 presents the energy consumption by energy source for "S" Elementary School before and after the introduction of the GSHP system. The shaded area indicated as (A) is the increased amount of electricity consumption after the introduction of the GSHP system, and the shaded area indicated as (B) is the reduced amount of gas energy consumption.

Fig. 5 shows the energy consumption by energy source of "I" Elementary School before and after the introduction of the GSHP system. The shaded area indicated as (A) is the reduced amount of electricity consumption after the introduction of the GSHP system.

5. Life cycle cost analysis

For LCC analysis, assumptions on various considerable factors are required [40]. First, the inflation rate, interest rate, the electricity price growth rate, the gas price growth rate, and the CO_2 emission trading price growth rate were determined, and the real discount rate was computed by applying them to Eq. (4). Based on the data provided by the Bank of Korea Economic Statistics System (ECOS) and the Korean Statistical Information Service (KOSIS) [41,42], the real discount rate on the inflation rate (3.30%), the electricity price growth rate (0.66%), the gas price growth rate (0.11%), and the CO_2 emission trading price growth rate (2.66%) were calculated, respectively, as follows:

$$i = \frac{(1+i_n)}{(1+f)} - 1 \tag{4}$$

where, i is the real discount rate, i_n is the nominal interest rate, and f is the inflation rate, the electricity price growth rate, the gas price growth rate, and the carbon dioxide emission trading price growth rate.

Second, the analysis period for LCC should be set. The two selected schools were both reinforced-concrete buildings. Thus, the service life of both buildings was set at 40 years, based on the service life of reinforced-concrete buildings in the standard service life and service life scope chart for buildings in the Enforcement Regulation of the Corporate Income Tax Act in South Korea [43]. As "S" Elementary School, however, was built in 2003 and is thus now 6 years old, its analysis period for LCC was set at 34 years. As for "I" Elementary School, it was established in 1982 and was extended and reconstructed in 1992, which extended the service life of the building. As such, the age of "I" Elementary School was set at 17 years, and its analysis period for LCC was set at 23 years.

Third, the significant cost of ownership had to be established for LCC analysis [44–46]. This includes the consideration of the initial investment cost, operation and maintenance cost, and demolition cost. It was assumed in this study, however, that the waste disposal cost set off the salvage value, which corresponds to two components of the demolition cost, for which reason the demolition cost was excluded from the analysis. Therefore, only the

Table 6
CO_2 emissions from the materials (or equipment) of the NRE systems.

Type	Phase	Materials (or Equipment)		"S" Elementary School		"I" Elementary School	
				Quantity of CO_2 emission by material (kg)	Sum of quantity of CO_2 emission by system (kg)	Quantity of CO_2 emission by material (kg)	Sum of quantity of CO_2 emission by system (kg)
PV	Preceding process	Waterproofing and grouting		650,976	3,898,737	607,577	3,714,905
	PV material	Module	Cell	1,219,402		1,163,975	
			Glass	180,166		171,977	
			Frame	184,798		176,398	
		Inverter		747,418		717,521	
		Connection box		16,243		16,243	
	PV construction	Steel structure (hot-dip galvanizing)		821,987		784,624	
		Power cable		47,875		47,875	
		Wire way		14,363		13,724	
		Other materials (bolt, nut, washer)		15,509		14,992	
GSHP	GSHP material	Heat pump		782,449	6,122,277	853,581	6,505,065
		Heat transfer circulating pump		68,906		82,687	
		Supplemental pump		7421		8905	
		Heat-charging water storage tank		5417		9849	
		Expansion tank		72,791		132,347	
	GSHP construction	Borehole		2,017,604		2,017,604	
		Black pipe casing		64,691		64,691	
		Vertical-loop piping		373,304		388,859	
		Geothermal-piping parts		135,126		128,984	
		Geothermal horizontal pipe		336,520		367,113	
		Antifreeze	PG	151,366		150,386	
		Grouting	Bentonite	108,640		114,072	
		Trench piping		127,470		127,470	
		Excavation and refilling	Fuel of equipment	160,484		192,581	
	Plumbing HVAC engineering	Copper pipe and component		1,051,626		1,147,228	
		Electrical devices		606,647		662,184	
		Other materials		51,816		56,527	

initial investment cost and operation and maintenance cost were considered in the LCC analysis. The details of the initial investment cost and operation and maintenance cost of NRE systems were from obtained an interview with an expert in the field of a leading manufacturer and supplier of NRE system in South Korea. Further, the amounts of energy produced by the PV and GSHP systems were calculated via energy simulation, and these were used as the bases of the energy cost out of the total operation cost.

Table 5 provides the significant cost of ownership for LCC analysis: the initial investment cost, government subsidy, repair cost and cycle, replacement cycle, and annual energy consumption of the PV and GSHP systems to be applied to "S" and "I" Elementary Schools. The detailed LCC analysis results are provided in the following sections.

6. Life cycle assessment

In this study, LCA was also conducted for the PV and GSHP systems. LCA is a methodology for analyzing the amount of CO_2 emissions for the entire life cycle of a building, from material production to waste disposal. It uses the LCI database, which lists the data regarding the amount of resources inputted and the wastes generated during the entire life cycle of a building, from the excavation of the raw materials to the final disposal of each product unit (function unit). It can be used to calculate the amount of CO_2 emitted to the environment. In this study, the LCI database developed by the Ministry of Environment, the Ministry of Knowledge Economy, and the Ministry of Land, Transport, and Maritime Affairs in South Korea was applied.

To conduct LCA, the material compositions of the NRE systems must be determined. The material compositions of the NRE systems were established according to their target generation that was reflected on the results of the energy simulation. These were organized based on the detailed bills of quantities obtained from the production factories and installation companies of the NRE systems. The amount of CO_2 emissions according to the fuel consumption of the equipment, which is used to construct the system, was also considered.

The LCA for the PV system was classified into the preceding process, the PV system materials, and the PV system construction. The preceding process consisted of waterproofing and grouping. The PV system materials included a module (cell, glass, and frame), an inverter, and a connection box. Finally, the PV system construction included a steel structure, a power cable, a wire way, and other materials.

The LCA for the GSHP system was classified into the GSHP equipment, GSHP construction, and plumbing HVAC engineering parts. The GSHP equipment included a heat pump, a heat transfer circulating pump, a supplementary pump, a heat-charging water storage tank, and an expansion tank. The GSHP construction included a borehole, a black pipe casing, a vertical-loop piping, geothermal-piping parts, a geothermal horizontal pipe, antifreeze, grouting, trench piping, and the fuel of the equipment for excavating and refilling (excavator). Finally, the plumbing HVAC engineering parts included a copper pipe and component, electrical tools, and other materials.

Table 6 shows the material compositions of the PV and GSHP systems, and the equipment used in their respective construction processes. The amounts of CO_2 emitted by the factors are provided by school.

7. Analysis of life cycle cost and life cycle CO_2

Based on the results of the previously conducted LCC and LCA, the economic and environmental effects of each NRE system were determined. First, in the economic aspect, the initial investment cost,

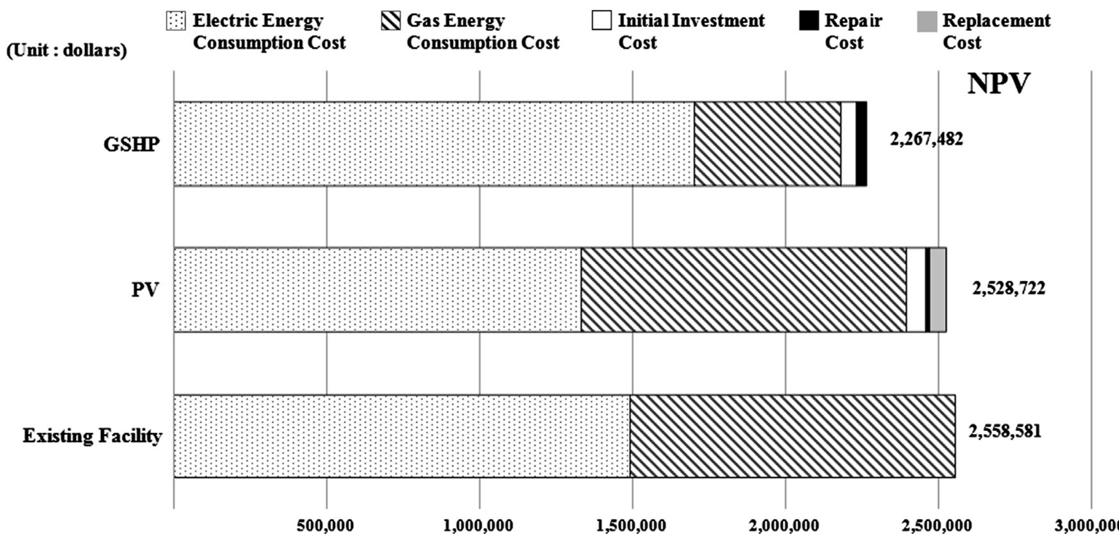

Fig. 6. Economic analysis for the NRE systems in "S" Elementary School (based on the NPV).

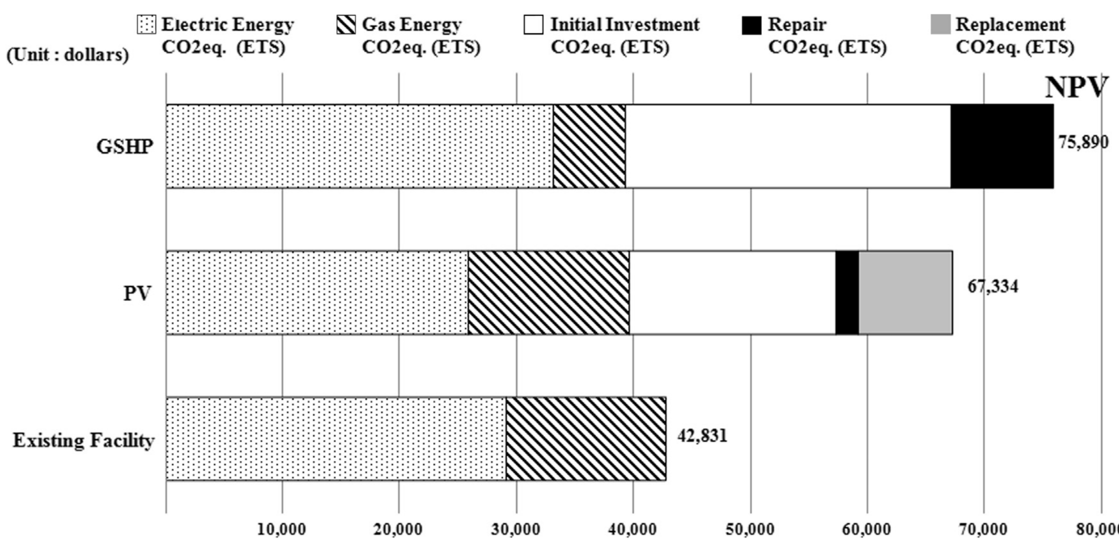

Fig. 7. Environmental analysis for the NRE systems in "S" Elementary School (based on the NPV).

maintenance cost for repair and replacement, and operation cost for electricity and gas energy consumption were considered. Second, in the environmental aspect, the amounts of CO_2 emissions by initial construction work, by repair and replacement work, and by electricity and gas consumption were considered. The total amount of CO_2 emissions over the entire life cycles of the schools were applied to the LCC and $LCCO_2$ analyses. The amounts of CO_2 emissions were converted to economic values using the profit from the sale of carbon credits, called "certified emission reductions (CERs)" (US\$4.55/tCO_2eq.) [47].

7.1. Net present value (NPV)

Net present value (NPV) is the difference between the present value of benefits and the present value of costs. NPV is used to analyze the absolute profitability of projects [48]. The profitability of the project is generally accepted when "NPV > 0" and when it is judged to occur the break-even point (BEP) within the analysis period. In this study, NPV was calculated using Eq. (5).

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{5}$$

where NPV is the net present value, B_t the benefit in year t, C_t the cost in year t, r the real discount rate, and n the LCA period.

7.1.1. Economic and environmental analysis on "S" elementary school using NPV

Figs. 6 and 7 show the results of the economic and environmental analyses that were conducted in this study with regard to the effects of the introduction of the PV and GSHP systems to "S" Elementary School.

Fig. 6 shows the results of the economic analysis based on the NPV. Compared to the existing facility, it was determined that the PV system saves US\$29,859 (NPV = US\$29,859) and that the GSHP system saves US\$291,099 (NPV = US\$291,099). The amount of cost saved by the PV system is largely inferior to that saved by the GSHP system. This is because the replacement of the PV system occurs within the LCC analysis period of 34 years as the end of service life of the PV system is 25 years. Further, the improvement effect of the GSHP system is very high. The previous studies suggested the efficiency of the cooling and heating systems to be in the order of GSHP > EHP > GHP [49].

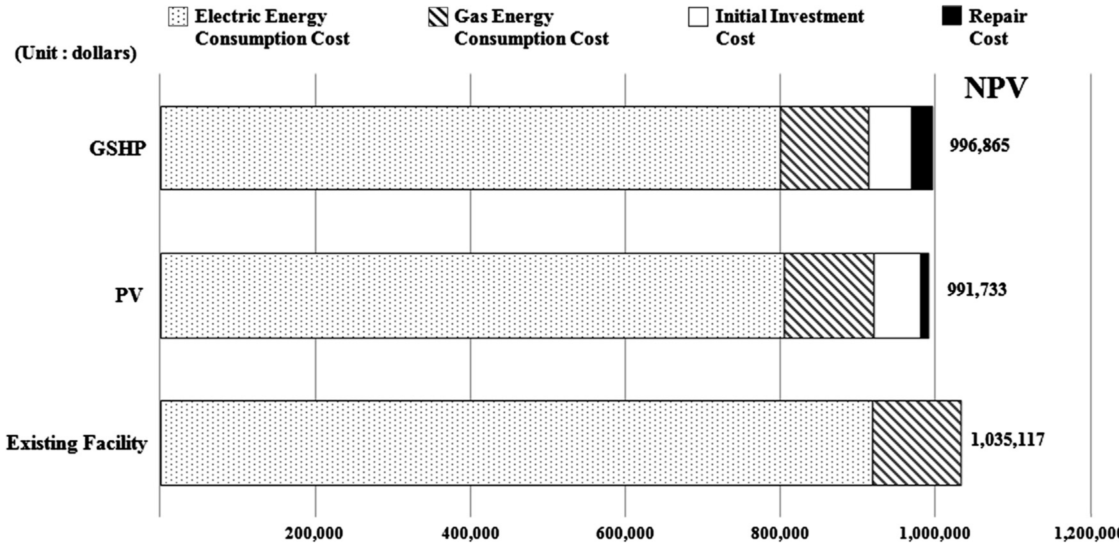

Fig. 8. Economic analysis for the NRE systems in "I" Elementary School (based on the NPV).

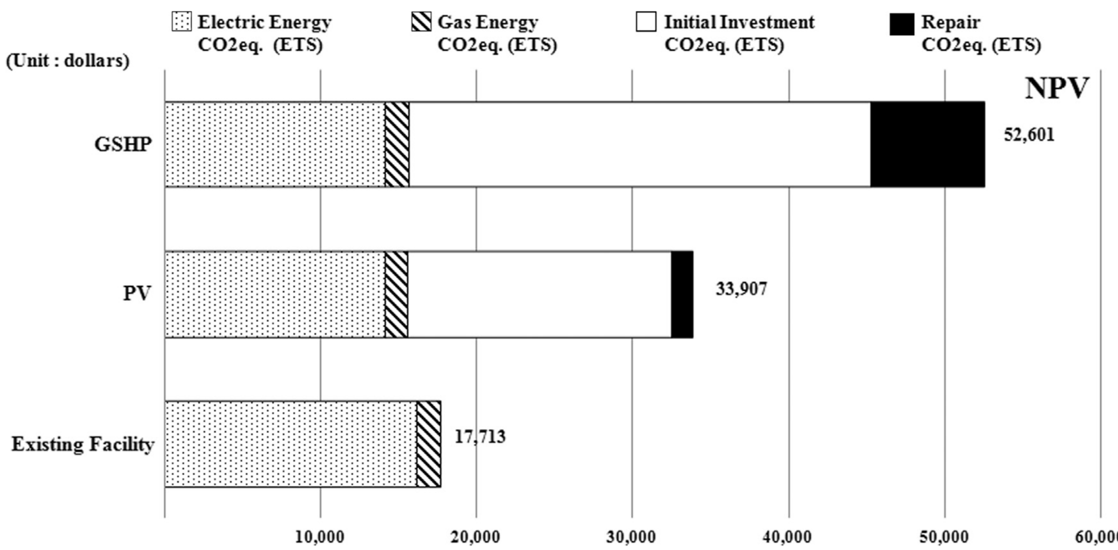

Fig. 9. Environmental analysis for the NRE systems in "I" Elementary School (based on the NPV).

Fig. 7 shows the results of the environmental analysis based on the NPV. Compared to the existing facility, it was determined that the PV system adds US$24,503 to the environmental cost (NPV= −US$24,503) and that the GSHP system adds US$33,059 to the same (NPV= −US$33,059). This is because the embedded CO_2 emissions by each material comprising the PV and GSHP systems are very high. Therefore, efforts should be exerted to reduce the amounts of CO_2 emitted in the production processes of the materials comprising the NRE system. Moreover, considering the trends of the reduction of the initial investment cost of the NRE system and the increase in its energy generation efficiency, the results of the environmental analysis are expected to gradually improve in the future [50–52].

7.1.2. Economic and environmental analysis on "I" elementary school using NPV

Figs. 8 and 9 show the results of the economic and environmental analyses that were conducted in this study with regard to the effects of the introduction of the PV and GSHP systems to "I" Elementary School.

Fig. 8 shows the results of the economic analysis based on the NPV. Compared to the existing facility, it was determined that the PV system saves US$43,384 (NPV=US$43,384) and that the GSHP system saves US$38,252 (NPV=US$38,252). The amount of cost saved by the PV system is slightly higher than that saved by the GSHP system. It is different from the result of the analysis on "S" Elementary School. This is because the replacement of the PV system does not occur within the LCC analysis period of 24 years for "I" Elementary School as the end of service life of the PV system is 25 years. Moreover, the improvement effect of the GSHP system is inadequate. That is, as the EHP system applied to the existing facility showed sufficient efficiency, the improvement effect of the introduction of the GSHP system is not large enough. The previous studies suggest the efficiency of the cooling and heating systems to be in the order of GSHP > EHP > GHP [49].

Fig. 9 shows the results of the environmental analysis based on the NPV. Compared to the existing facility, it was determined that the PV system adds US$16,194 to the environmental cost (NPV= −US$16,194) and that the GSHP system adds US$34,388 to the same (NPV= −US$34,888). This is because the embedded CO_2 emissions by each material comprising the PV and GSHP systems are very high. Therefore, efforts should be exerted to reduce the

Table 7
SIR of the PV and GSHP systems from the economic and environmental points of view.

	Year		1	2	3	4	5	6	7	8	9	10
"S" Case	PV	Economic analysis	0.08	0.17	0.25	0.32	0.40	0.48	0.55	0.62	0.69	0.76
		Economic and environmental analysis	0.07	0.13	0.20	0.26	0.32	0.38	0.44	0.50	0.55	0.61
	GSHP	Economic analysis	0.20	0.39	0.58	0.75	0.92	1.08	1.23	1.38	1.53	1.67
		Economic and environmental analysis	0.13	0.26	0.38	0.50	0.61	0.72	0.83	0.93	1.03	1.13
"I" Case	PV	Economic analysis	0.09	0.17	0.25	0.34	0.41	0.49	0.57	0.64	0.71	0.79
		Economic and environmental analysis	0.07	0.14	0.20	0.27	0.33	0.39	0.45	0.51	0.57	0.63
	GSHP	Economic analysis	0.10	0.19	0.28	0.36	0.44	0.52	0.59	0.66	0.73	0.79
		Economic and environmental analysis	0.07	0.13	0.19	0.24	0.30	0.35	0.40	0.45	0.50	0.54

	Year		11	12	13	14	15	16	17	18	19	20	21	22	23
"S" Case	PV	Economic analysis	0.83	0.90	0.96	1.03	1.09	1.15	1.21	1.27	1.33	1.39	1.45	1.51	1.57
		Economic and environmental analysis	0.66	0.72	0.77	0.82	0.87	0.92	0.97	1.02	1.07	1.12	1.17	1.22	1.26
	GSHP	Economic analysis	1.80	1.94	2.07	2.20	2.33	2.45	2.57	2.69	2.81	2.93	3.05	3.16	3.28
		Economic and environmental analysis	1.23	1.32	1.41	1.51	1.59	1.68	1.77	1.86	1.94	2.03	2.11	2.19	2.28
"I" Case	PV	Economic analysis	0.86	0.92	0.99	1.06	1.12	1.19	1.25	1.32	1.38	1.44	1.50	1.56	1.62
		Economic and environmental analysis	0.69	0.74	0.80	0.85	0.91	0.96	1.01	1.06	1.11	1.16	1.21	1.26	1.31
	GSHP	Economic analysis	0.85	0.91	0.97	1.03	1.08	1.13	1.18	1.23	1.28	1.33	1.38	1.43	1.47
		Economic and environmental analysis	0.58	0.63	0.67	0.71	0.75	0.78	0.82	0.86	0.89	0.93	0.96	1.00	1.03

	Year		24	25	26	27	28	29	30	31	32	33	34
"S" Case	PV	Economic analysis	1.62	0.94	0.98	1.01	1.04	1.07	1.10	1.13	1.17	1.20	1.23
		Economic and environmental analysis	1.31	0.84	0.87	0.90	0.92	0.95	0.98	1.01	1.03	1.06	1.09
	GSHP	Economic analysis	3.39	3.51	3.62	3.73	3.84	3.95	4.06	4.17	4.28	4.39	4.50
		Economic and environmental analysis	2.36	2.44	2.52	2.60	2.68	2.76	2.84	2.92	3.00	3.07	3.15
"I" Case	PV	Economic analysis											
		Economic and environmental analysis											
	GSHP	Economic analysis											
		Economic and environmental analysis											

Note: The shaded areas stands for the periods with "SIR > 1" where the BEP is generated. They sometimes do not continuously appear due to the replacement of the NRE systems.

quantities of CO_2 emitted in the production processes of the materials comprising the NRE system. The initial investment cost of the NRE system, however, is continuously decreasing, and its energy generation efficiency is growing. Considering these, it is expected that the result of the environmental analysis will gradually improve in the future [50–52].

7.2. Saving to investment ratio (SIR)

The savings-to-investment ratio (SIR) method is the ratio of the present value of savings to the present value of investments. SIR is used to analyze the relative profitability of projects [48]. When "SIR ≥ 1," the profitability of the project is accepted. In LCC analysis, while the NPV method is an absolute evaluation method, the SIR method is a relative one. Table 7 shows the results of the economic and environmental analyses for the PV and GSHP systems using the SIR method. The SIR was calculated using Eq. (6).

$$SIR = \frac{\sum_{t=0}^{n} \frac{S_t}{(1+r)^t}}{\Sigma_{t=0}^{n} I_t/(1+r)^t} \tag{6}$$

where, SIR is the savings-to-investment ratio, S_t the savings in year t, I_t the investment in year t, r the real discount rate, and n the LCA period.

7.2.1. Economic and environmental analyses on "S" elementary school using SIR

First, it was determined from the economic analysis that "SIR ≥ 1" appeared in the14th year after the introduction of the PV system. Namely, the BEP (SIR = 1.03) occurs. As the PV system, however, was replaced in the 25th year, "SIR < 1" in the 25th and 26th years; as such the BEP did not occur. Nevertheless, the BEP reappeared in the 27th year due to energy-saving effect. In the comprehensive evaluation of the economic and environmental effects, it was determined that "SIR ≥ 1" was achieved in the 18th years after the PV system is introduced. Namely, the BEP (SIR = 1.02) occurs. As with the result of the economic analysis, however, the PV system is replaced in the 25th year; as such, the BEP does not occur within the period between the 25th and 30th years. Nevertheless, the BEP reappears in the 31st year due to the energy-saving and environmental-cost-saving effects. In this study, in the comprehensive evaluation of the economic analysis along with environmental analysis, the BEP appeared at a later time. As with the result of the NPV analysis, this was because the environmental cost was added due to the embedded CO_2 emissions by material.

Second, it was determined in the economic analysis for the GSHP system that "SIR ≥ 1" appeared in the 6th year after the introduction of the system. Based on the comprehensive evaluation results in both the economic and environmental aspects, however, "SIR ≥ 1" appeared in the 9th year, which was three years later. Namely, the BEP (SIR = 1.08 and 1.03, respectively) occurred. This is because the environmental cost was added due to the embedded CO_2 emissions by material.

7.2.2. Economic and environmental analyses on "I" elementary school using SIR

First, the results of the economic analysis for the PV system showed that "SIR ≥ 1" appeared in the 14th year after the introduction of the system. Based on the comprehensive evaluation results in both the economic and environmental aspects, however, "SIR ≥ 1" appeared in the 17th year, which was three years later. Namely, the BEP (SIR = 1.06 and 1.01, respectively) occurred. This is because the environmental cost was added due to the embedded CO_2 emissions by material.

Second, the results of the economic analysis for the GSHP system showed that "SIR ≥ 1" appeared in the 14th year after the introduction of the system. Based on the comprehensive evaluation results in both the economic and environmental aspects, however, "SIR ≥ 1" appeared in the 22nd year, which was eight years later. Namely, the BEP (SIR = 1.03 and 1.00, respectively) occurred. This is because the environmental cost was added due to the embedded CO_2 emissions by material.

8. Conclusions and discussion

This study aimed to evaluate the economic and environmental effects of NRE systems for the selection of the optimum NRE system for educational facilities. By conducting a multilateral analysis on the results of the energy simulation, the energy generation (or substitution) effect was evaluated by applying the PV and GSHP systems as NRE systems. Furthermore, LCC analysis, including the analysis of the $LCCO_2$ (e.g., the embedded CO_2 emissions by material or CO_2 emissions by energy consumption), was conducted to assess the economic and environmental effects of the introduction of the NRE systems, using several methods, such as the NPV and SIR methods.

The effects of the introduction of the NRE system to "S" and "I" Elementary School were evaluated through an economic- and environmental-assessment proposed in the study. First, the evaluation results for "S" Elementary School are shown below.

- According to the economic evaluation, the BEP is generated in the 14th year after the introduction of the PV system, and in the 6th year after the introduction of the GSHP system.
- According to the economic and environmental evaluation, the BEP is generated in the 18th year after the introduction of the PV system, and in the 9th year after the introduction of the GSHP system.
- The PV system was applied to "S" Elementary School, but the study results showed that the application of the GSHP system is more beneficial to the school in both the economic and environmental aspects.
- These results prove the necessity of the economic and environmental evaluation proposed in this study.

Second, the evaluation results for "I" Elementary School are shown below.

- The economic evaluation showed that both the BEPs are generated in the 14th year after the introduction of the PV and GSHP systems.
- The economic and environmental evaluation showed that both the BEPs are generated in the 17th and 22nd year, after the introduction of the PV and GSHP systems, respectively.
- The PV system was applied to "I" Elementary School, and the study results showed that it is more beneficial to apply such system than the GSHP system in the school in both the economic and environmental aspects.
- As these results are different from the results for "S" Elementary School, it shows that the optimal NRE system can be differentiated according to the characteristics of the existing facility.

Third, the results of the economic evaluation for both facilities were found to be superior to the results of the economic and environmental evaluation. This is because the embedded CO_2

emissions by material comprising the NRE system are very high and is not covered by the energy-saving effect.

In this study, economic and environmental evaluation was conducted for the PV and GSHP systems, and the following multi-dimensional analyses are suggested to be performed in the future studies: (i) various analyses of other NRE systems, such as the STE and WE systems; (ii) sensitivity analysis of the NRE systems considering the recent trends in the reduction of the initial investment cost and in the improvement of the energy generation efficiency; and (iii) comparative analysis of the effects of introducing energy-saving measures (ESMs) and NRE systems. With regard to this, the development of an optimum design model for the NRE systems using a genetic algorithm is under way.

It is expected that the results of this study can be used to (i) determine which NRE system is most appropriate for a specific facility; (ii) calculate the payback period for a certain investment; (iii) decide which location is proper for the implementation of the NRE system considering the characteristics of the regional climate; and (iv) select energy- and cost-efficient elementary schools where the NRE system can be applied.

Acknowledgments

This research was supported by a Grant from High-Tech Urban Development Program (10CHUD-C03) funded by the Ministry of Land, Transport and Maritime affairs, South Korea. This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korea government (MSIP; Ministry of Science, ICT & Future Planning) (No. 2012–004376 and No. 2012–0001247).

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